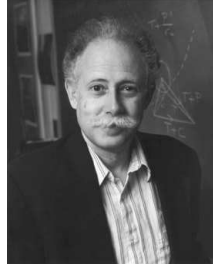


MORIOND QCD 2007 – THEORY SUMMARY

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Developments reported at the 2007 Moriond Workshop on QCD and Hadronic Interactions are reviewed and placed in a theoretical context.

1 Introduction

QCD was invented in 1973. (There were some earlier hints.) We are still concerned with it as neither perturbative nor currently available non-perturbative (e.g., lattice) methods apply to many interesting phenomena. These include hadron structure, spectroscopy, jet and quarkonium fragmentation, heavy ion physics, and effects of thresholds. The understanding of hadronic behavior is crucial in separating underlying short-distance physics (whether electroweak or new) from strong-interaction effects. The properties of hadrons containing heavy quarks provide an exceptional window into QCD tests. Finally, QCD may not be the only instance of important non-perturbative effects; familiarity with it may help us to prepare for surprises at the Large Hadron Collider (LHC). In this review we shall discuss a number of developments reported at Moriond QCD 2007 in the context of these ideas. A companion review¹ deals directly with the experimental results. I apologize for not covering some theoretical topics whose relation to experimental results presented at this conference is not yet clear to me, and for omitting some nice experimental results for which I have no comments.

2 Heavy flavor issues: the current CKM matrix

The Kobayashi-Maskawa matrix theory of CP violation, and its parametrization of charge-changing weak transitions, as shown in Fig. 1, passes all experimental tests so far. The major uncertainties in the parameters of the CKM matrix are now dominated by theory. Briefly, we have $V_{ud} \simeq V_{cs} \simeq 0.974$, $V_{us} \simeq -V_{cd} \simeq 0.226$, $V_{cb} \simeq -V_{ts} \simeq 0.041$, $V_{td} \simeq 0.008e^{-i 21^\circ}$,

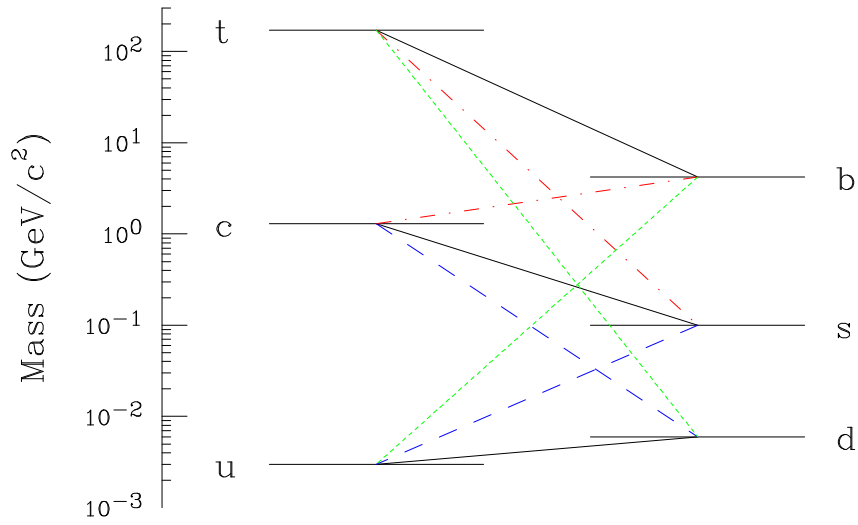


Figure 1: The quarks and weak charge-changing transitions among them. Solid, dashed, dash-dotted, and dotted lines correspond to successively weaker transitions.

$V_{ub} \simeq 0.004e^{-i 66^\circ}$ (sources of phase information will be explained below), and – on the basis of single-top production observed by the D0 collaboration² – $0.68 < |V_{tb}| < 1$ at 95% c.l.

3 Meson decay constants and implications

The ability of theory to anticipate important hadronic properties is illustrated by recent results on meson decay constants. Moreover, it has been possible in some cases to replace calculated quantities with better-determined experimental ones, reducing errors on fundamental parameters such as CKM matrix elements.

In 2005 the CLEO Collaboration³ reported the measurement $f_{D^+} = (222.6 \pm 16.7_{-3.4}^{+2.8})$ MeV, to be compared with one lattice QCD prediction⁴ of $201 \pm 3 \pm 17$ MeV. More recently CLEO has measured $f_{D_s} = (274 \pm 13 \pm 7)$ MeV.⁵ [One can obtain a slightly more precise value by including preliminary data on $D_s \rightarrow \tau \nu$ where $\tau \rightarrow e \nu \bar{\nu}$.⁶] The BaBar Collaboration reports $f_{D_s} = (283 \pm 17 \pm 7 \pm 14)$ MeV.⁷

One lattice prediction⁴ is $f_{D_s} = 249 \pm 3 \pm 16$ MeV, leading to a predicted ratio $f_{D_s}/f_D = 1.24 \pm 0.01 \pm 0.07$. This is to be compared with the CLEO ratio $1.23 \pm 0.11 \pm 0.04$.⁵ One expects $f_{B_s}/f_B \simeq f_{D_s}/f_D$ so better measurements of f_{D_s} and f_D by CLEO will help validate lattice calculations and provide input for interpreting B_s mixing. A desirable error on $f_{B_s}/f_B \simeq f_{D_s}/f_D$ is $\leq 5\%$ for a useful determination of the CKM element ratio $|V_{td}/V_{ts}|$. This will require errors ≤ 10 MeV on f_{D_s} and f_D . (Independent information on $|V_{td}/V_{ts}|$ has come from a precise measurement of B_s – \bar{B}_s mixing.⁸) A scaling argument from the quark model⁹ implies $f_{D_s}/f_D \simeq f_{B_s}/f_B \simeq \sqrt{M_s/M_d} \simeq 1.25$, with constituent masses $M_s \simeq 485$ MeV, $M_d \simeq 310$ MeV.

4 B_s physics

Comparing box diagrams for $b\bar{s} \rightarrow s\bar{b}$ and $b\bar{d} \rightarrow d\bar{b}$ (dominated by intermediate top quarks), one sees that B_s – \bar{B}_s mixing is stronger than B – \bar{B} mixing because $|V_{ts}/V_{td}| \simeq 5$. Now, CKM unitarity implies $|V_{ts}| \simeq |V_{cb}| \simeq 0.041$ is well measured, so B_s – \bar{B}_s mixing really probes the matrix element between B_s and \bar{B}_s . This quantity involves $f_{B_s}^2 B_{B_s}$, whose ratio with respect to that for non-strange B 's is known from lattice QCD:¹⁰ $\xi \equiv f_{B_s} \sqrt{B_{B_s}} / (f_B \sqrt{B_B}) = 1.21_{-0.035}^{+0.047}$. The B^0 – \bar{B}^0 mixing amplitude is well-measured: $\Delta m_d = (0.507 \pm 0.004)$ ps⁻¹. Consequently,

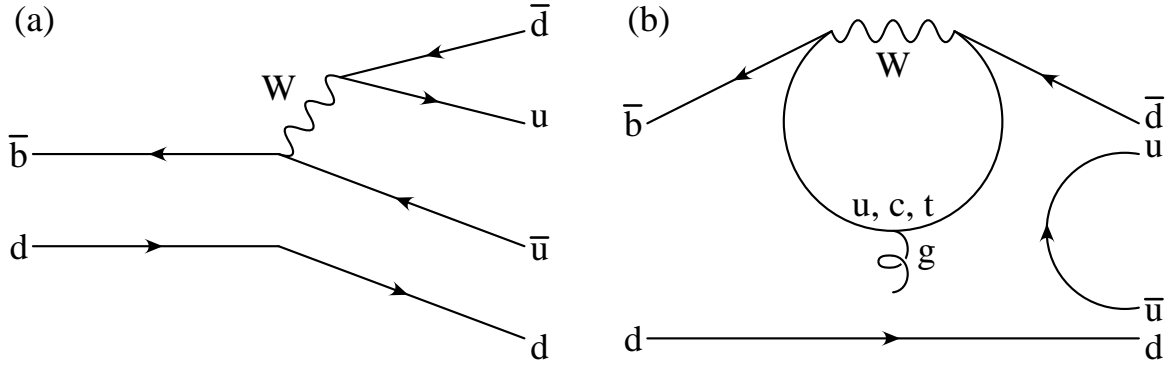


Figure 2: Examples of decay topologies for $B^0 \rightarrow \pi^+ \pi^-$. (a) Tree; (b) penguin.

measurement of B_s mixing implies a value of $|V_{td}/V_{ts}|$. The recent CDF measurement at Fermilab $\Delta m_s = (17.77 \pm 0.10 \pm 0.07) \text{ ps}^{-1}$ ⁸ gives $|V_{td}/V_{ts}| = 0.206 \pm 0.008$ and hence $1 - \rho - i\eta \equiv |V_{tb}^* V_{td}/(V_{cb}^* V_{cd})| = 0.91 \pm 0.04$. This implies that $\gamma \equiv \text{Arg}(V_{ub}^* V_{ud}/(V_{cb}^* V_{cd})) \simeq (66 \pm 6)^\circ$, a great improvement over previous determinations.

The first evidence for B_s mixing was presented by the D0 collaboration.¹¹ This collaboration has now presented evidence for a decay rate difference between the B_s mass eigenstates, with the eigenstate which is approximately CP-even decaying somewhat more rapidly:¹² $\Delta\Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1}$. This agrees with the expected value¹³ $\Delta\Gamma_s \simeq (1/200)\Delta m_s \simeq 0.09 \text{ ps}^{-1}$. (The values of $\Delta\Gamma_s$ and Δm_s are expected to track one another.) Within large errors, D0 sees no evidence for CP violation in $B_s \rightarrow J/\psi\phi$. One expects in the Standard Model $\phi_s = 0.036 \pm 0.003$, a value which may be accessible to LHCb.^{14,15}

5 Systematics of B decays

5.1 General considerations

Reviews of B decays were given at this Conference by Lin¹⁶ (experiment) and Lü¹⁷ (theory). It is useful to visualize B decay amplitudes in terms of flavor diagrams¹⁸ (see, e.g., Fig. 2). Flavor SU(3) permits one to relate decay asymmetries in one channel to those in another. For example, one can show^{19,20}

$$\Gamma(\bar{B}^0 \rightarrow \pi^+ \pi^-) - \Gamma(B^0 \rightarrow \pi^+ \pi^-) = -[\Gamma(\bar{B}^0 \rightarrow K^- \pi^+) - \Gamma(B^0 \rightarrow K^+ \pi^-)] . \quad (1)$$

Using dominance of $B \rightarrow K\pi$ transitions by the isospin-preserving ($\Delta I = 0$) penguin $\bar{b} \rightarrow \bar{s}$ transition, and a well-established hierarchy of other amplitudes, one can obtain sum rules for rates²¹ and asymmetries^{22,23} in these decays. Defining the CP-averaged ratios

$$R \equiv \frac{\bar{\Gamma}(B^0 \rightarrow K^+ \pi^-)}{\bar{\Gamma}(B^+ \rightarrow K^0 \pi^+)} , \quad R_c \equiv \frac{2\bar{\Gamma}(B^+ \rightarrow K^+ \pi^0)}{\bar{\Gamma}(B^+ \rightarrow K^0 \pi^+)} , \quad R_n \equiv \frac{\bar{\Gamma}(B^0 \rightarrow K^+ \pi^-)}{2\bar{\Gamma}(B^0 \rightarrow K^0 \pi^0)} \quad (2)$$

where $\bar{\Gamma}(B \rightarrow f) \equiv [\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})]/2$, one such sum rule is $R_c = R_n$. Experimentally²⁴

$$R = 0.90 \pm 0.05 , \quad R_c = 1.11 \pm 0.07 , \quad R_n = 0.97 \pm 0.07 , \quad (3)$$

so the sum rule is satisfied. It is expected to hold also to first order in isospin breaking.²⁵

A recent result is relevant to the systematics of $B \rightarrow PV$ decays, where P and V are light pseudoscalar and vector mesons. The pure penguin process $B^+ \rightarrow K^0 \rho^+$ has been seen by BaBar²⁶ with a branching ratio $\mathcal{B}(B^+ \rightarrow K^0 \rho^+) = (8.0_{-1.3}^{+1.4} \pm 0.5) \times 10^{-6}$. This is comparable

to the pure-penguin process $B^+ \rightarrow K^{*0}\pi^+$ with $\mathcal{B} = (10.7 \pm 0.8) \times 10^{-6}$. In the former process, the spectator quark ends up in a vector meson (“ p_V ”), while in the latter the spectator ends up in a pseudoscalar (“ p_P ”). This confirms an early expectation by Lipkin²⁷ that the amplitudes for the two processes were related by $p_V \simeq -p_P$.

5.2 B_s decays

One way to learn the width difference $\Delta\Gamma$ of B_s mass eigenstates is to compare the decay lifetimes in different polarization states of the final vector mesons in $B_s \rightarrow J/\psi\phi$. These are conveniently expressed in a Cartesian basis.²⁸ There are three such states. Two are CP-even. In one of these, the vector mesons’ linear polarizations are perpendicular to the decay axis and parallel to one another (“ \parallel ”). In the other CP-even state, both vector mesons are longitudinally polarized (“0”). In the CP-odd state, the vector mesons’ linear polarizations are perpendicular to the decay axis and also to one another (“ \perp ”). Separating out the CP-even and CP-odd lifetimes would be much easier using \parallel and \perp states, thereby avoiding bias due to imperfect modeling of polar angle dependence.

The branching ratio $\mathcal{B}(B_s \rightarrow K^+K^-) = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$ reported by CDF at this Conference²⁹ is due mainly to the $|\Delta S| = 1$ penguin. For comparison, $\mathcal{B}(B^+ \rightarrow K^0\pi^+) = (23.1 \pm 1.0) \times 10^{-6}$. The large error on the former means that one can’t see the effects of non-penguin amplitudes through interference with the dominant penguin.

B_s decays help validate flavor-SU(3) techniques used in extracting CKM phases. For example, under the U-spin transformation $d \leftrightarrow s$, the decay $B_s \rightarrow K^-\pi^+$ is related to $B^0 \rightarrow K^+\pi^-$. It has a branching ratio of $(5.0 \pm 0.75 \pm 1.0) \times 10^{-6}$; it differs from the process $B^0 \rightarrow \pi^+\pi^-$ with $\mathcal{B} = (5.16 \pm 0.22) \times 10^{-6}$ only by having a different spectator quark.

5.3 Baryonic B decays

Results presented at this conference^{30,31,32} shed light on the mechanisms of B decays to baryonic final states. Low-mass baryon-antibaryon enhancements seen in these decays favor a fragmentation picture over resonant substructure, based in part on information from angular correlations between decay products. The production of several heavy quarks, as in $b \rightarrow cs\bar{c}$, helps produce baryons like csq where $q = (u, d)$ gives Ξ_c and $q = s$ gives Ω_c . The large available phase space and high quark multiplicity in B decays may permit the production of exotic final states.³³

5.4 Sum rules for CP asymmetries in $B \rightarrow K\pi$

Using the dominance of the $\Delta I = 0$ $\bar{b} \rightarrow \bar{s}$ penguin amplitude, M. Gronau²² has shown that

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) = A_{CP}(K^+\pi^0) + A_{CP}(K^0\pi^0) . \quad (4)$$

Non-penguin amplitudes should be small in $B^+ \rightarrow K^0\pi^+$, so $A_{CP}(K^0\pi^+) \simeq 0$ and²³

$$A_{CP}(K^+\pi^-) = A_{CP}(K^+\pi^0) + A_{CP}(K^0\pi^0) . \quad (5)$$

[Strictly speaking, a more accurate version of these sum rules applies to CP-violating rate differences $\Delta(f) \equiv \Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)$.] The observed CP asymmetries²⁴ are $A_{CP}(K^+\pi^-) = -0.097 \pm 0.012$, $A_{CP}(K^0\pi^+) = 0.009 \pm 0.025$, $A_{CP}(K^+\pi^0) = 0.047 \pm 0.026$, and $A_{CP}(K^0\pi^0) = -0.12 \pm 0.11$. The last is the most poorly known and may instead be predicted using the sum rules. With corrections for $\tau(B^+)/\tau(B^0) = 1.076 \pm 0.008$ and branching ratios, the first and second of these sum rules predict $A_{CP}(K^0\pi^0) = (-0.140 \pm 0.043, -0.150 \pm 0.035)$. The experimental value of $A_{CP}(K^0\pi^0)$ carries too large an error at present to provide a test.

A vanishing $A_{CP}(K^0\pi^0)$ would imply $A_{CP}(K^+\pi^-) = A_{CP}(K^+\pi^0)$, which is not so. $A_{CP}(K^+\pi^0)$ and $A_{CP}(K^0\pi^0)$ involve color-suppressed tree and electroweak penguin (EW) amplitudes. The latter occur in a calculable ratio $\delta_{EW} = 0.60 \pm 0.05$ with respect to known amplitudes.

One may ask how the CP asymmetry in $B^0 \rightarrow K^+\pi^-$ can be non-zero, thereby signaling the presence of non-penguin amplitudes, while neither the CP asymmetry nor the rate ratio R_c shows evidence of such amplitudes in $B^+ \rightarrow K^+\pi^0$. Let $r_c \sim 0.2$ denote the ratio of tree to penguin amplitudes in $B^+ \rightarrow K^+\pi^0$. One may write the sum rule³⁴

$$\left(\frac{R_c - 1}{\cos \gamma - \delta_{EW}}\right)^2 + \left(\frac{A_{CP}(B^+ \rightarrow K^+\pi^0)}{\sin \gamma}\right)^2 = (2r_c)^2 + \mathcal{O}(r_c^3), \quad (6)$$

which is essentially based on the identity $\cos^2 \delta + \sin^2 \delta = 1$, where δ is a strong phase. The key to this sum rule's validity is that $\cos \gamma \simeq \delta_{EW}$, thereby allowing it to be satisfied for $R_c \simeq 1$ and small $A_{CP}(K^+\pi^0)$.

5.5 Ways to measure $\sin 2\beta$

The BaBar Collaboration has updated its value based on $b \rightarrow c\bar{c}s$ decays:³⁵ $\sin 2\beta = 0.714 \pm 0.032 \pm 0.018$. When combined with the latest Belle value³⁶ of $0.642 \pm 0.031 \pm 0.017$ and earlier data this gives a world average^{24,37} $\sin 2\beta = 0.678 \pm 0.025$, serving as a reference for all other determinations of β .

Recently BaBar studied in the decay $B^0 \rightarrow D_{CP}^{(*)0}h^0$, extracting coefficients S and C of time-dependent decay rate modulations proportional to $\sin \Delta mt$ and $\cos \Delta mt$.³⁸ The result $\sin 2\beta_{\text{eff}} = -S = 0.56 \pm 0.23 \pm 0.05$ is compatible with the reference value. The value $C = -0.23 \pm 0.16 \pm 0.04$ is compatible with no direct CP violation, as expected in the Standard Model, but carries a large experimental error.

A large number of processes are dominated by $b \rightarrow s$ penguin amplitudes. When averaged,²⁴ these give $\sin 2\beta_{\text{eff}} = 0.53 \pm 0.05$, a value 2.6σ below the reference value. It is not clear that it makes sense to average all these processes as some involve $b \rightarrow s\bar{s}s$, others $b \rightarrow s\bar{d}d$ and/or $b \rightarrow s\bar{u}u$, and some involve mixtures. Moreover, QCD corrections can differ for different final states. The experimental values have shifted a good deal from year to year, providing theorists with a moving target which they have been quite adept at following. At present the number on which I am keeping an eye is that from $B^0 \rightarrow \pi^0 K_S$, which both BaBar and Belle agree lies below the reference value, with an average $\sin 2\beta_{\text{eff}} = 0.33 \pm 0.21$. (Note the large experimental error.) The value of the $\cos \Delta mt$ coefficient $C_{K_S\pi^0} = 0.12 \pm 0.11$ also is interesting. This is just $-A_{CP}(K^0\pi^0)$. As noted earlier, sum rules predict a central value of 0.14 to 0.15 for $C_{K_S\pi^0}$.

Many estimates have been performed of deviations of $\sin 2\beta_{\text{eff}}$ from the reference value in the Standard Model. Typical explicit calculations give a deviation of 0.05 or less, usually predicting $\sin 2\beta_{\text{eff}}$ *larger* than 0.678 whereas most experiments find *lower* values. Flavor-SU(3) estimates³⁹ allow differences of at most 0.1.

5.6 CP violation in $B \rightarrow \pi\pi$

An example of the systematic error associated with uncertainty in hadron physics is provided by a detailed examination of time-dependent CP asymmetries in $B^0 \rightarrow \pi^+\pi^-$. This is relevant to remarks made by Lü¹⁷ at this Conference concerning limitations in our ability to learn the weak phases α and γ . I report on work with M. Gronau,⁴⁰ updating a previous analysis.⁴¹

The time-dependent asymmetry parameters ($S_{\pi\pi}, C_{\pi\pi}$) have been measured by BaBar⁴² ($-0.60 \pm 0.11, -0.21 \pm 0.09$) and Belle⁴³ ($-0.61 \pm 0.11, -0.55 \pm 0.09$), leading to an average²⁴ ($-0.605 \pm 0.078, -0.376 \pm 0.066$). These average values are plotted in Fig. 3 along with predictions for values of the weak phase α and strong phase $\delta = \delta^P - \delta^T$. An SU(3)-breaking factor

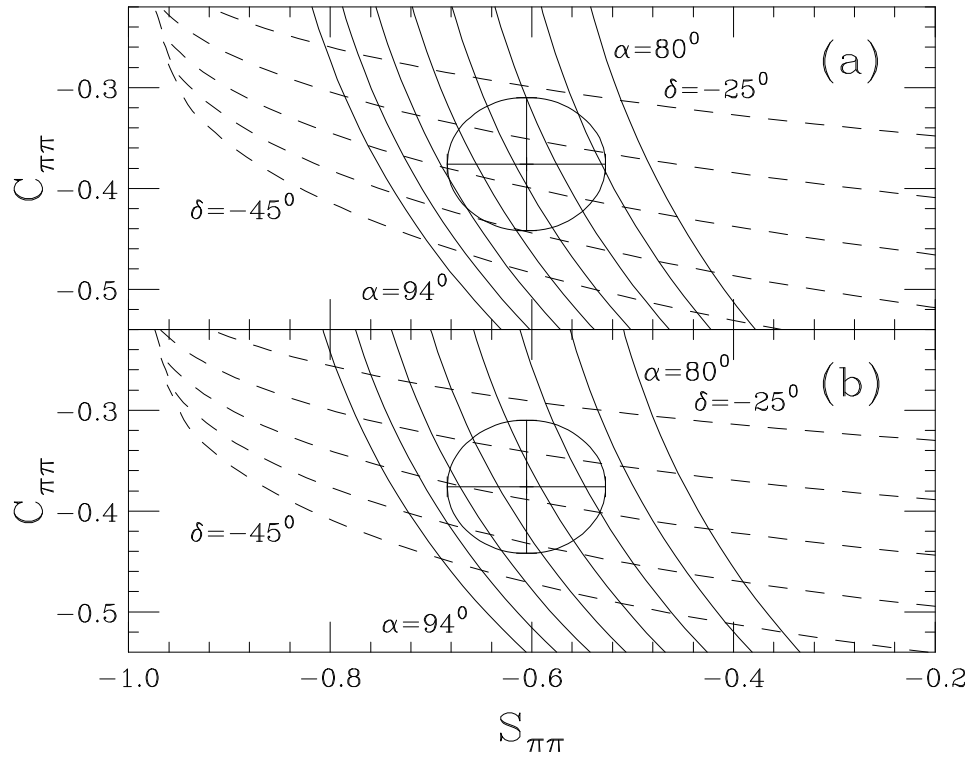


Figure 3: Values of $C_{\pi\pi}$ plotted against $S_{\pi\pi}$ for values of α spaced by 2 degrees (solid curves) and δ spaced by 5 degrees (dashed contours). The degree of penguin “pollution” is estimated in (a) from $B^+ \rightarrow K^0 \pi^+$ and in (b) from $B^0 \rightarrow K^+ \pi^-$.

$f_K/f_\pi = 1.22$ has been taken for the ratio of $|\Delta S| = 1$ to $\Delta S = 0$ tree amplitudes, but no SU(3) breaking has been assumed for the corresponding ratio of penguin amplitudes. The error ellipses represented by the plotted points encompass the ranges $81^\circ \leq \alpha \leq 91^\circ$ (implying $68^\circ \leq \gamma \leq 78^\circ$) and $-40^\circ \leq \delta \leq -26^\circ$. As in Ref.⁴⁴, we get a very small range of γ [here $(73 \pm 4)^\circ$], but additional systematic errors are important. In the upper figure, the penguin “pollution” has been estimated using $B^+ \rightarrow K^0 \pi^+$, entailing the neglect of a small “annihilation” amplitude, while in the lower figure it has been estimated using $B^0 \rightarrow K^+ \pi^-$, in which the effect of a small tree amplitude must be included. The two methods give weak phases within a degree or two of one another.

Now we examine the effect of SU(3) breaking in the ratio of penguin amplitudes. Call the $\Delta S = 0$ penguin P , the $|\Delta S| = 1$ penguin P' , and define $\xi_P \equiv |P'/P| V_{cd}^* V_{cb} / V_{cs}^* V_{cb}|$. The above exercise was for $\xi_P = 1$. Now we vary ξ_P .

One could assume $\xi_P = f_K/f_\pi = 1.22$ as for the tree amplitude ratio.⁴⁴ Alternatively, one could determine it from $\Delta(K^+ \pi^-) = -\xi_P \Delta(\pi^+ \pi^-)$, where $\Delta(f) \equiv \Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)$. In this case with the world average $A_{CP}(K^+ \pi^-) = -0.097 \pm 0.012$ one finds $\xi_P = 0.79 \pm 0.18$.

The change from $\xi_P = 1$ to $\xi_P = 1.22$ shifts α up (γ down) by $\sim 8^\circ$, $|\delta|$ up by $\sim 10^\circ$, while the change to $\xi_P = 0.79$ shifts α down (γ up) by $\sim 10^\circ$, $|\delta|$ down by $\sim 8^\circ$. The systematic (theory) errors are larger than the statistical ones. As stressed by Lü,¹⁷ one needs to gain control of SU(3) breaking. In order to provide information beyond that obtained from flavor SU(3), schemes such as PQCD¹⁷ and SCET⁴⁵ need to predict δ to better than 10° .

Discussion at this Conference concerned the relative merits of frequentist⁴⁶ and Bayesian⁴⁷ analysis, referring to a recent controversy over what can be learned from $B \rightarrow \pi\pi$.⁴⁸ The intelligent choice of priors can have merits, e.g., when searching for a point on the surface of a sphere (taking a uniform prior in the cosine of the polar angle θ , not θ itself) or when searching for a lost skier at La Thuile (beginning by looking near the lifts).

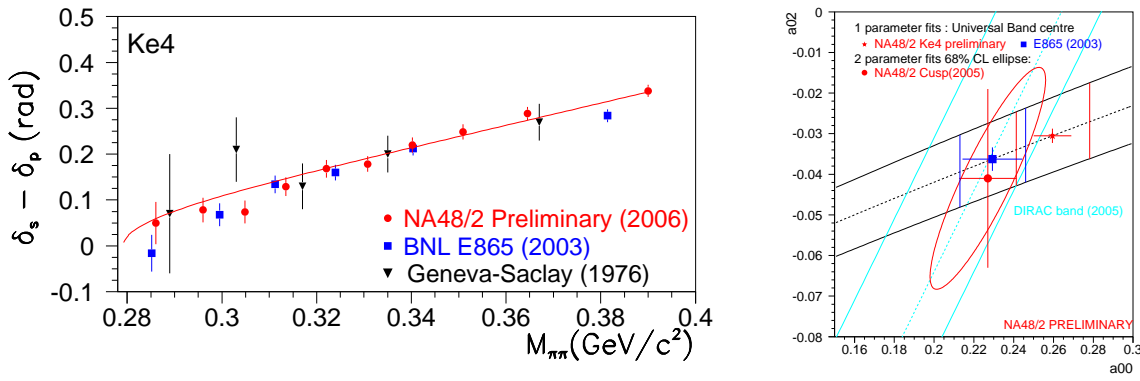


Figure 4: Information on $\pi\pi$ scattering from NA48 and other sources.⁵⁸ Left: K_{e4} decays; right: $\pi\pi$ scattering lengths.

6 D mixing

In the Standard Model, mixing due to shared intermediate states reached by $|\Delta C| = 1$ transitions dominates D^0 - \bar{D}^0 mixing. In the flavor-SU(3) limit these contributions (e.g., $\pi\pi$, $K\bar{K}$, $K\pi$, and $\bar{K}\pi$) cancel one another.⁴⁹ How precise is the cancellation?

Define D_1 and D_2 to be the mass eigenstates (respectively CP-even and -odd in the absence of CP violation), $\Delta M \equiv M_1 - M_2$, $\Delta\Gamma \equiv \Gamma_1 - \Gamma_2$, $x \equiv \Delta M/\Gamma$, and $y \equiv \Delta\Gamma/\Gamma$, where $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$. Estimates of y range up to $\mathcal{O}(1\%)$, with $|x| \leq |y|$ typically.

The time dependence of “wrong-sign” $D^0(t=0)$ decays (e.g., to $K^+\pi^-$) involves the combinations $x' \equiv x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$, $y' \equiv -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}$, where the strong phase $\delta_{K\pi}$ has been measured by the CLEO Collaboration:⁵⁰ $\cos \delta_{K\pi} = 1.09 \pm 0.66$. In the SU(3) limit, $\delta_{K\pi} = 0$.⁵¹ This method has been used by the BaBar Collaboration^{52,53} to obtain the non-zero mixing parameter $y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$.

The Belle Collaboration has obtained evidence for mixing in a different way, by comparing lifetimes in CP- and flavor-eigenstates and thereby measuring a parameter $y_{CP} = (1.13 \pm 0.32 \pm 0.25)\%$.^{54,55} In the limit of CP conservation (a likely approximation for D mesons), $y_{CP} = y$. A time-dependent Dalitz plot analysis of $D^0 \rightarrow K_S \pi^+ \pi^-$ by Belle^{55,56} obtains $x = (0.80 \pm 0.29^{+0.09+0.15}_{-0.04-0.14})\%$, $y = (0.33 \pm 0.24^{+0.07+0.08}_{-0.12-0.09})\%$.

These results were synthesized in several theoretical analyses.⁵⁷ The consensus is that while y is near the upper limit of what was anticipated in the Standard Model, there is no evidence for new physics. Observation of CP violation in D decays, on the other hand, would be good evidence for such physics, and will continue to be the object of searches.

7 Low-energy hadron physics

Information on light-quark interactions and spectroscopy continues to accumulate from weak decays of kaons, charm (telling about the low-mass $I = J = 0$ dipion resonance σ), and B (illuminating properties of scalar mesons like f_0 and a_0 , which must be understood if one is to identify glueballs), and radiative ϕ decays. For example, the NA48 Collaboration at CERN has obtained information on $\pi\pi$ scattering lengths from K_{e4} and $K^+ \rightarrow \pi^+ \pi^0 \pi^0$ decays.⁵⁸ Some results are summarized in Fig. 4.

Scattering lengths a_J^I are conventionally labelled by total momentum J and isospin I . The predictions of current algebra⁵⁹ are $a_0^2 = -0.044$ and $a_0^0 = 0.22$. The NA48 measurement of a_0^0 seems to be slightly above this last value but more data from NA48 will tell whether there really is a discrepancy.

The helicity structure of ρ mesons in the reaction $e^+e^- \rightarrow \rho^+\rho^-$ has recently been measured by the BaBar Collaboration,⁶⁰ with the result $F_{00} = 0.54 \pm 0.10 \pm 0.02$, where the subscripts denote ρ helicity. This is to be compared with the asymptotic prediction⁶¹ $F_{00} \rightarrow 1$. Should one be surprised? Are there related tests at comparable scales of $E_{\text{cm}} \simeq 10$ GeV?

Recent results by the KLOE Collaboration^{62,63} shed light on the quark/gluon content of η' through the decay $\phi \rightarrow \eta'\gamma$. Comparison of this decay with others (such as $\phi \rightarrow \eta\gamma$, $\rho \rightarrow \eta\gamma$, $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \gamma\gamma$, and so on), following a method proposed some time ago,⁶⁴ lead to the conclusion that the glue content of the η' is $(14 \pm 4)\%$.

8 Charmonium

Results from BES were presented at this Conference^{65,66} on states reached in J/ψ decays, including a broad $X(1580)$ decaying to K^+K^- seen in $J/\psi \rightarrow K^+K^-\pi^0$ and an $\omega\phi$ threshold peak seen in $J/\psi \rightarrow \gamma\omega\phi$, as well as on multibody $\psi(2S)$ decays. CLEO results^{67,68} included confirmation of the $Y(4260)$ in a direct scan and in radiative return; a new measurement of $M(D^0)$ which implies that the $X(3872)$ is bound by 0.6 ± 0.6 MeV; and observation of $\psi''(3770) \rightarrow \gamma\chi_c$ decays with rates confirming its assignment as the 1^3D_1 charmonium state. Belle⁶⁹ reported two-photon production of several states including $Z(3930)$, a $\chi_{c2}(2P)$ candidate.

9 Charmed hadrons

9.1 $L = 0$ states

BaBar^{70,71} has identified the Ω_c^* , a candidate for the lowest-lying $J = 3/2$ $c\bar{s}s$ state lying $70.8 \pm 1.0 \pm 1.1$ MeV above the Ω_c (also recently studied by BaBar⁷²). This mass splitting agrees with that predicted in the quark model.⁷³ One now has a complete set of candidates for the $L = 0$ mesons and baryons containing a single charmed quark. As we shall see, charmed hadron masses are useful in anticipating those of hadrons containing a b quark.

9.2 Orbitally-excited mesons

In the heavy-quark limit, mesons made of one heavy and one light quark are best described by coupling the light quark and the orbital angular momentum L to a total j , and then j to the heavy quark spin to form states of $J = j \pm 1/2$. For $L = 1$ one then has states with $j = 1/2$ (leading to $J = 0, 1$) and $j = 3/2$ (leading to $J = 1, 2$). The $J = 3/2$ states, predicted to be narrow, have been known for many years for both charmed-nonstrange and charmed-strange mesons. However, the $j = 1/2$ states, expected to be broad, proved more elusive.

The two $L = 1$, $j = 1/2$ $c\bar{s}$ mesons, the $D_{s0}(2317)$ and $D_{s1}(2460)$, were lighter than expected by most theorists. Lying below the respective DK and D^*K thresholds for strong decays, they turned out to be narrow, decaying radiatively or via isospin-violating π^0 emission. Their low masses *were* anticipated in schemes which pegged them as chiral partners of the D_s and D_s^* .⁷⁴ Regarding them as bound states of DK and D^*K , respectively, they each would have a binding energy of 41 MeV. It would be interesting to see if a similar pattern holds for B_{sJ} as $\bar{B}^{(*)}K$ bound states. The lesson is that light-quark degrees of freedom appear to be important in understanding heavy-quark systems.

Higher-mass $c\bar{s}$ states have now been reported.⁷⁵ The Belle Collaboration⁷⁶ sees a D_s state in the $M(D^0K^+)$ spectrum in $B^0 \rightarrow \bar{D}^0D^0K^+$. It has $M = (2715 \pm 11_{-14}^{+11})$ MeV and $\Gamma = (115 \pm 20_{-32}^{+36})$ MeV. BaBar could be seeing this state, though not with significance.⁷⁷ It has $J^P = 1^-$ and lies 603_{-18}^{+16} MeV above $D_s^*(2112)$, to be compared with $2S$ – $1S$ splittings of 681 ± 20 MeV for $s\bar{s}$ and 589 MeV for $c\bar{c}$. It appears to be a good $c\bar{s}(2^3S_1)$ candidate.

Another D_s state is seen decaying to $D^0 K^+$ and $D^+ K_S$.⁷⁷ It has $M = (2856.6 \pm 1.5 \pm 5.0)$ MeV and $\Gamma = (48 \pm 7 \pm 10)$ MeV. It can be interpreted as the first radial excitation of $D_{s0}(2317)$ ⁷⁸ or a $J^P = 3^-(^3D_3)$ state.⁷⁹ Angular distributions of decay products should permit a distinction.

While the established (narrow) $j^P = 3/2^+$ states $D_1(2422)$, $D_2(2460)$ have been known for quite some time, there is more question about the broad $j^P = 1/2^+$ candidates. Both CLEO⁸⁰ and Belle⁸¹ place the broad $j^P = 1/2^+$, $J^P = 1^+$ candidates in the narrow range 2420–2460 MeV, but Belle⁸¹ and FOCUS⁸² differ somewhat with respect to broad $j^P = 1/2^+$, $J^P = 0^+$ candidates, placing them only in a rather wide range 2300–2400 MeV.

One feature of note is that orbital excitation to the well-established $j = 3/2$ states costs (472,482) MeV for (D^{**}, D_s^{**}) . We shall compare this figure with a corresponding one for B mesons.

10 Beauty hadrons

10.1 $L = 0$ states

CDF has observed Σ_b and Σ_b^* candidates decaying to $\pi^\pm \Lambda_b^0$.^{83,84} Their mass measurements are aided by a new precise value, also due to CDF,⁸⁵ $M(\Lambda_b) = (5619.7 \pm 1.2 \pm 1.2)$ MeV. It is worth comparing this mass with a simple quark model prediction.

The light (u, d) quarks in Λ_c and Λ_b must be coupled to spin zero, by the requirements of Fermi statistics, as they are antisymmetric in color (3^*) and flavor ($I = 0$) and symmetric in space (S-wave). Aside from small binding effects, one then expects $M(\Lambda_b) - M(\Lambda_c) = M_b - M_c$, where M_b and M_c are “constituent” quark masses whose difference $M_b - M_c$ may be obtained from $B^{(*)}$ and $D^{(*)}$ mesons by taking the combinations $(3M^* + M)/4$ for which the hyperfine $Q\bar{q}$ interactions cancel. Using $[3M(B^*) + M(B)]/4 = 5314.6 \pm 0.5$ MeV and $[3M(D^*) + M(D)]/4 = 1973.0 \pm 0.4$ MeV one then finds $M_b - M_c = 3341.6 \pm 0.6$ MeV. (This is slightly larger than the difference between $M_b = 4796$ MeV and $M_c = 1666$ MeV reported by Kühn.⁸⁶) Combining this difference with $M(\Lambda_c) = 2286.46 \pm 0.14$ MeV, one then predicts $M(\Lambda_b) = 5628.1 \pm 0.7$ MeV, 8 MeV above the observed value. One could ascribe the small difference, which goes in the right direction, to reduced-mass effects. A similar exercise predicts $M(\Xi_b) \simeq 5.8$ GeV from $M(\Xi_c) = 2469$ MeV.

We now turn to the $\Sigma_b^{(*)}$ states. The direct measurements are of $Q^{(*)\pm} \equiv M(\Sigma_b^{(*)\pm}) - M(\pi^\pm) - M(\Lambda_b)$, and it is found (under the assumption $Q^{*+} - Q^{*-} = Q^+ - Q^-$, which is expected to be good to 0.4 MeV⁸⁷) that

$$Q^+ = 48.4 \pm_{2.3}^{+2.0 \pm 0.2} \text{ MeV}, \quad Q^- = 55.9 \pm 1.0 \pm 0.2 \text{ MeV}. \quad (7)$$

With the new CDF value of $M(\Lambda_b)$, these results then imply

$$M(\Sigma_b^-) = 5815.2 \pm_{0.9}^{+1.0} \pm 1.7 \text{ MeV}, \quad M(\Sigma_b^+) = 5807.5 \pm_{2.2}^{+1.9} \pm 1.7 \text{ MeV}, \quad (8)$$

$$M(\Sigma_b^{*-}) = 5836.7 \pm_{2.3}^{+2.0 \pm 1.8} \text{ MeV}, \quad M(\Sigma_b^{*+}) = 5829.0 \pm_{1.7}^{+1.6 \pm 1.7} \text{ MeV}. \quad (9)$$

These masses are entirely consistent with quark model predictions. (See⁸⁷ and references therein.) The Λ hyperon may be denoted $[ud]s$, where $[ud]$ denotes a pair antisymmetric in flavor and spin, whereas the $\Sigma^{+,0,-}$ quark wavefunction may be written as $(\cdot\cdot)s$, with $(\cdot\cdot) = (uu), (ud), (dd)$ shorthand for a pair *symmetric* in flavor and spin. $S(\cdot\cdot) = 1$ then can couple with $S(s) = 1/2$ to give $J = 1/2$ (Σ) or $3/2$ (Σ^*), with hyperfine splitting $\propto 1/m_s$. The mass difference between the spin-1 and spin-0 diquarks, $M(\cdot\cdot) - M[ud] = [2M(\Sigma^*) + M(\Sigma)]/3 - M(\Lambda)$, can be calculated from the spin-weighted average of $M(\Sigma^*)$ and $M(\Sigma)$, in which hyperfine interactions cancel out. This result is the same calculated from baryons containing s , c , or b :

$$\frac{\Sigma + 2\Sigma^*}{3} - \Lambda = 205.1 \pm 0.3 \text{ MeV} \cdot \frac{\Sigma_c + 2\Sigma_c^*}{3} - \Lambda_c = 210.0 \pm 0.5 \text{ MeV}, \quad (10)$$

Table 1: Candidates for $L = 1$, $j^P = 3/2^+$ B mesons. Masses in MeV.

	Nonstrange		Strange	
	B_1	B_2	B_{s1}	B_{s2}
CDF	$5738 \pm 5 \pm 1$	$5734 \pm 3 \pm 2$	$5829.2 \pm 0.2 \pm 0.6$	$5839.6 \pm 0.4 \pm 0.5$
D0	$5720.8 \pm 2.5 \pm 5.3$	$5746 \pm 2.4 \pm 5.4$	–	$5839.1 \pm 1.4 \pm 1.5$

to be compared with

$$\frac{\Sigma_b + 2\Sigma_b^*}{3} - \Lambda_b = 205.9 \pm 1.8 \text{ MeV} . \quad (11)$$

The hyperfine splittings themselves also obey reasonable scaling laws. One expects $M(\Sigma^*) - M(\Sigma) \propto 1/m_s$ so splittings for charm and bottom should scale as $1/m_c$, $1/m_b$, respectively. The differences for s , c , and b , 191.4 ± 0.4 , 64.4 ± 0.8 , 21.3 ± 2.0 MeV, are indeed approximately in the ratio of $1/m_s : 1/m_c : 1/m_b$.

10.2 $L = 1$ mesons

Results from CDF and D0, summarized by Filthaut,⁸⁴ are shown in Table 1. Arguments similar to those for the $L = 0$ baryons in the previous subsection imply that one should expect $M(B_2) - M(B_1) \simeq M(B_{s2}) - M(B_{s1}) \simeq 13$ MeV. This pattern does not seem to emerge clearly from the data, which in any case give mixed signals regarding hyperfine splittings. One pattern which does seem fairly clear is that orbital $j = 3/2$ B , B_s excitations cost ~ 50 MeV less than for D , D_s .

11 Importance of thresholds

Many hadrons discovered recently require that one understand nearby thresholds, a problem with a long history.^{88,89,90} As one example, the cross section for $e^+e^- \rightarrow (\text{hadrons})$ has a sharp dip around a center-of-mass energy of 4.25 GeV, which is just below the threshold for the lowest-lying pair of charmed mesons (D^0 and \bar{D}_1^{*0}) which can be produced *in a relative S-wave*. All lower-mass thresholds, such as $D\bar{D}$, $D\bar{D}^*$, and $D^*\bar{D}^*$, correspond to production in relative P-waves, so the corresponding channels do not open up as quickly. The $D^0\bar{D}_1^{*0}$ (+ c.c.) channel is the expected decay of the puzzling charmonium state $Y(4260)$ if it is a hybrid ($c\bar{c} + \text{gluon}$). But this channel is closed, so others (such as the observed $\pi\pi J/\psi$ channel) may be favored instead.

It is likely that the dip in $e^+e^- \rightarrow (\text{hadrons})$ is correlated with a substantial suppression of charm production just before the $D^0\bar{D}_1^{*0}$ channel opens up. The cross section for $e^+e^- \rightarrow D^*\bar{D}^*$ (a major charm channel) indeed experiences a sharp dip at 4.25 GeV.⁹¹ Perhaps the peak $Y(4320) \rightarrow \pi^+\pi^-\psi(2S)$ seen by BaBar,⁹² with $M = 4324 \pm 24$ MeV, $\Gamma = 172 \pm 33$ MeV, is correlated with some other threshold.

Many other dips are correlated with thresholds [e.g., in the $\pi\pi$ S-wave near $2M(K)$ or $\gamma^* \rightarrow 6\pi$ near $2M(p)$.⁹³] The BaBar Collaboration recently has reported a structure in $e^+e^- \rightarrow \phi f_0(980)$ at 2175 MeV.⁹⁴ It could be a hybrid $s\bar{s}g$ candidate in the same way that $Y(4260)$ is a hybrid $c\bar{c}g$ candidate. The assignment makes sense if $M_c - M_s \simeq (M_Y - M_X)/2 = 1.04$ GeV.

12 Quark masses

J. H. Kühn⁸⁶ has presented explicit formulae for the running of quark masses. High-order corrections to the Taylor series for the heavy quark vacuum polarization function $\Pi_Q(q^2)$ are a *tour de force*. [One may expect interesting things from this group on high-order corrections

to $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.] The moments $\mathcal{M}_n = \int ds R(s)/s^{n+1}$ give consistent masses, with $m_c(m_c) = 1287 \pm 13$ MeV from $n = 1$ and $m_b(m_b) = 4167 \pm 23$ MeV from $n = 2$. These results are an update of Ref. ⁹⁵. The pole masses $M_b = 4796$ MeV and $M_c = 1666$ MeV differ by 3130 MeV, a bit less than the phenomenological value of 3342 MeV mentioned earlier in the prediction of $M(\Lambda_b)$. One caveat is that old CLEO data were used with an arbitrary renormalization. CLEO should come out soon with new R values below $B\bar{B}$ threshold but needs to present its data above $B\bar{B}$ threshold similarly. These data were taken in connection with a search for $\Lambda_b\bar{\Lambda}_b$ production. ⁹⁶

A. Pineda has reminded me of a work ⁹⁷ in which $\bar{m}_b(\bar{m}_b) = 4.19 \pm 0.06$ GeV is obtained from a non-relativistic sum rule. Kühn's talk has a compilation of many other values. The uncertainty in m_c , reduced by Kühn's analysis, is an important part of the theoretical error in calculating $\mathcal{B}(b \rightarrow s\gamma)$. ⁹⁸

Although the top quark mass has been measured with impressive accuracy (see below), it may be possible by studying threshold behavior in $e^+e^- \rightarrow t\bar{t}$ to learn it to about 0.1 GeV. ⁹⁹

13 Heavy flavor production

Calculations of hadronic charm production are in rough accord with experiment (though there remains some excess peaking for small azimuthal angle between charm and anticharm). While the description of beauty production has improved vastly in the past few years, there are still some kinematic regions where experiment exceeds theory. ¹⁰⁰ Incisive beauty–antibeauty correlation measurements still do not exist despite long-standing pleas. ¹⁰¹ One looks forward to these at the LHC. ¹⁰²

The quantitative understanding of quarkonium production still seems elusive. It demands soft gluon radiation, “adjustable” to the observed cross section. This is not the same as a first-principles calculation.

14 Fragmentation and jets

The correct description of fragmentation was a key ingredient in improving the agreement of b production predictions with experiment. ¹⁰⁰ At this conference new and/or upgraded Monte Carlo routines were reported. ^{103,104} A useful detailed check of their hadronization features would be to compare their predicted multiplicities and particle species with CLEO data on hadronic χ_c decays ⁶⁸ or hadronic bottomonium decays (which are being analyzed by CLEO). One could also imagine applying the global determination of fragmentation functions reported by Kumano ¹⁰⁵ to these questions.

Progress also has been reported with spinor-based multigluon methods; ^{106,107} definition of b -jets; ¹⁰⁸ correction for the underlying event; ¹⁰⁹ exclusive $p\bar{p} \rightarrow p\bar{p}X$ reactions; ¹¹⁰ inclusive cross sections; ^{111,112} and an infrared-safe jet definition. ¹¹³ Jets in heavy-ion collisions will be especially challenging. ¹¹⁴

15 W and top

New CDF values of ($M_W = 80413 \pm 48$) MeV and $\Gamma_W = (2032 \pm 71)$ MeV have recently been reported. ¹¹⁵ The new world averages, $M_W = 80398 \pm 25$ MeV and $\Gamma_W = (2095 \pm 47)$ MeV, are consistent with the Standard Model. In the latter there is very little room for deviations since no “oblique” (S, T) corrections are expected: ¹¹⁶

$$\Gamma(W) = \frac{G_\mu M_W^3}{6\pi\sqrt{2}} \left\{ 3 + 6 \left[1 + \frac{\alpha_S(M_W)}{\pi} \right] \right\} = (2100 \pm 4) \text{ MeV} . \quad (12)$$

Now information on top quark mass and production comes from CDF and D0.¹¹⁷ Examples of new measurements in the $\ell + \text{jets}$ channel are $m_t = (170.5 \pm 2.4 \pm 1.2) \text{ GeV}$ (D0) and $(170.9 \pm 2.2 \pm 1.40) \text{ GeV}$ (CDF). The present world average is now $m_t = (170.9 \pm 1.8) \text{ GeV}$, an error of 1.1%. This places further pressure on the Higgs mass. The Standard Model fit gives $M_H \leq 144 \text{ GeV}$ (95% c.l.), relaxed to 182 GeV if the present direct limit $M_H > 114.4 \text{ GeV}$ is considered.

One alternative to a light Higgs boson would involve custodial symmetry violation [for example, as provided by a new heavy SU(2) doublet with large mass splitting].¹¹⁸ Adding a vacuum expectation value $\langle V_0 \rangle$ of a Higgs triplet with zero hypercharge which is only a few percent of the standard doublet $v = 246 \text{ GeV}$ would be sufficient to substantially relax the upper limit on M_H .¹¹⁹

The D0 Collaboration sees single-top production at the expected level in three different analyses.² CDF sees it in one analysis but not in two others.¹²⁰ When the dust settles, this measurement is expected to provide useful information on $|V_{tb}|$.

16 Dibosons and Higgs

CDF and D0 have presented evidence for WZ and ZZ production, as summarized by F. Würthwein.¹²¹ D0 has seen a dip corresponding to the expected radiation zero in $W\gamma$ production. The subprocess $u\bar{d} \rightarrow W^+\gamma$ has a zero at $\cos\theta_{\text{CM}} = -1/3$, while $\bar{u}d \rightarrow W^-\gamma$ has a zero at $\cos\theta_{\text{CM}} = 1/3$.

In a search for the Higgs boson in the $H \rightarrow \tau\tau$ channel, bounds from CDF are “degraded” thanks to an excess of events for $M_H \simeq 160 \text{ GeV}$. On the other hand, D0 sees a deficit there.¹²² This mass range may be the first interval accessible with 8 fb^{-1} at the Tevatron; sensitivities are improving faster than $1/\sqrt{\int \mathcal{L} dt}$.¹²³ It would be wonderful if a way were found to extend the run!

An interesting scheme for generating the Higgs boson via spontaneous conformal symmetry breaking was presented.¹²⁴ As this tends to give a fairly heavy Higgs boson, it must be confronted with the tightening precision electroweak constraints. Strong electroweak symmetry breaking scenarios also were described.¹²⁵ These essentially adapt chiral models to the TeV scale, replaying the strong interactions at a factor $v/f_\pi \simeq 2650$ higher in energy. Light-Higgs scenarios are not ruled out; for instance, it has been asked whether the mass of the $b\bar{b}(1^1S_0)$ state, the as-yet-unseen η_b , is standard or is affected by mixing with a light Higgs boson.¹²⁶ One Standard Model prediction^{127,128} is $M(\eta_b) = 9421 \text{ MeV}$.

Higgs decays to multiparticle final states have been described using twistor methods.¹⁰⁷ It may be possible to produce a Higgs boson at LHC in the double-diffractive reaction $pp \rightarrow ppH$, monitoring the small-angle protons using Roman pots.¹¹⁰ One problem will be distinguishing which of the multiple interactions per crossing was the source of the scattered protons. This pileup effect may be soluble if one can make sufficiently rapid trigger decisions.

Two-Higgs models, if confirmed, provide a gateway to supersymmetry.¹²⁹ Such proliferation of the Higgs spectrum, entailing two charged and three neutral Higgs bosons, also is a feature of grand unified theories beyond the minimal SU(5), such as SO(10).

17 Proton structure and diffraction

The proton spin $\frac{1}{2}$ is composed of $\frac{1}{2}\Delta\Sigma + \Delta G + \Delta L$, corresponding respectively to quarks, gluons, and orbital angular momentum. $\Delta\Sigma \simeq 0.3$; what’s the rest? The COMPASS¹³⁰ and STAR¹³¹ Collaborations have shown that ΔG is not enough; one must have $\Delta L > 0$.

Neutral-current ep interactions at HERA have displayed the first evidence for parity violation in high- Q^2 deep inelastic scattering.¹³² HERA is helping to pin down structure functions and their evolution for use at the LHC.¹³³ Also at HERA, it has been found that the Pomeron slope is different in ρ^0 and J/ψ photoproduction. These reactions correspond respectively to soft and hard processes.¹³⁴

18 Heavy ion collisions

One has seen the adaptation of string theory ideas to properties of the quark-gluon plasma: hydrodynamic properties involve previously intractable strong-coupling calculations.¹³⁵ In heavy-ion jet production, the recoiling jet is quenched if it must pass through the whole nucleus.¹¹⁴ This provides information about the properties of nuclear matter. An interesting rapidity “ridge” is seen in many processes. Could this be a manifestation of QCD “synchrotron radiation”? Do previous emulsion experiments¹³⁶ display this feature?

One way to describe nuclear matter effects is via medium-modified fragmentation functions probe nuclear matter effects.^{137,138} Useful information is provided by $\gamma\pi^0$ and $\gamma\gamma$ correlations.¹³⁸ Hanbury-Brown-Twiss correlations between identical particles (e.g., $\pi^\pm\pi^\pm$) provide information on the viscosity of the quark-gluon plasma and on the geometry and time evolution of the “hot” region.¹³⁹

Charmed particles are found to interact with the nuclear medium in the same way as others.¹⁴⁰ It is not clear whether there is a difference between the interactions of $c\bar{q}$ and $\bar{c}q$ states; certainly K^+ and K^- do interact differently with nonstrange matter. Other important issues in nuclei include low- x parton saturation¹⁴¹ and the question of whether quarkonium suppression is taking place.¹⁴²

19 Beyond the Standard Model

As this is a large field, I would like to comment on just a few items which I consider especially worth watching in the next few years.

(1) The muon’s $g-2$ value can get big contributions in some SUSY models. In units of 10^{-11} , $a_\mu \equiv (g_\mu - 2)/2 = 116\,591\,793\,(68)$ (theory), to be compared with $116\,592\,080\,(63)$ (experiment). These differ by (287 ± 93) or 3.1σ .¹⁴³ This relies upon evaluating hadronic vacuum polarization via e^+e^- annihilation. If one uses τ decays the discrepancy drops to 1.2σ . The inconsistency is worth sorting out.

(2) Non-standard explanations abound for the deviation of the effective $\sin(2\beta)$ in $b \rightarrow s$ penguins from the “reference value” obtained in decays dominated by $b \rightarrow c\bar{c}s$. The current biggest discrepancy is in $S_{\pi^0 K_S} = 0.33 \pm 0.21$, versus a nominal value of 0.678 ± 0.026 . This could be due, for instance, to exchange of a new Z' masquerading as an electroweak penguin.¹⁴⁴ The study of $b \rightarrow s\ell^+\ell^-$ and searches at the Tevatron and LHC will see or bound Z' effects. Forward-backward asymmetries can be quite sensitive to Z' s.^{145,146} One will be able to study such asymmetries at the LHC by passing to non-zero pseudorapidity η .¹⁴⁷

The $b \rightarrow s\ell^+\ell^-$ decays show no anomalous behavior so far.²⁹ Belle/BaBar differ a bit and CDF agrees with BaBar with $\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-) = (0.82 \pm 0.31 \pm 0.10) \times 10^{-6}$, and with Belle with $\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-) = (0.60 \pm 0.15 \pm 0.04) \times 10^{-6}$.

(3) It is encouraging to see the results searches for a right-handed W :^{120,148} $M_{W_R} > (790, 760)$ MeV for $M_{W_R}(<, >)M_{\nu_R}$. The case of a right-handed ν_R heavier than M_{W_R} , in particular, means that one must search for W_R in the hadronic channel $t\bar{b}$.¹⁴⁹

20 Dark matter in many forms

Ordinary matter exists in several stable forms: p , n (when incorporated into nuclei), e^- , three flavors of neutrinos [$\tau(\nu_{2,3}) \gg \tau(\text{Universe})$]. We could expect dark matter ($5\text{--}6 \times$ ordinary matter) to exhibit at least as much variety, for example if its quantum numbers are associated with a big gauge group largely shielded from current observations.¹⁵⁰ “Mirror particles,” reviewed extensively by Okun,¹⁵¹ are one example of this possibility.

There are at least two well-motivated dark matter candidates already (axions and neutralinos). Axion dark matter has not received the attention it deserves. RF cavity searches are going slowly; there is a large range of frequencies still to be scanned with enough sensitivity. Some variants of supersymmetry have long-lived next-to-lightest superpartners, decaying to the lightest superpartners over a detectable distance. Charged and neutral quasi-stable candidates¹⁵² could be split by so little that they charge-exchange with the detector, implying new tracking signatures.

Dark matter could have non-zero charges purely in a hidden sector and thus be invisible to all but gravitational probes. Such opportunities might be provided by the LISA detector.¹⁵³

Experience with hadron physics may help us deal with unexpected dark matter forms and interactions. This could be so, for example, if investigations at the TeV scale uncover a new strongly-interacting sector, as expected in some theories of dynamical electroweak symmetry breaking.

21 Outlook

Impressive measurements from BaBar, Belle, CDF, CERN NA48, CLEO, D0, KLOE, RHIC, and other experiments have provided much fuel for theoretical interpretations at this conference. The understanding of hadron physics plays a key role. Much knowledge about fundamental electroweak interactions relies on separating out the strong interactions. Methods include theoretical calculations (pQCD, SCET) and correlation of measurements through flavor symmetry. Conversely, low-energy hadron physics has benefitted greatly from weak interactions; K , D , B decays have provided information on $\pi\pi$ scattering, σ and other scalar mesons, and patterns of final-state interactions which go beyond what perturbative methods can anticipate.

Experiments at the Tevatron have shown that one can do excellent flavor physics in a hadronic environment. We look forward to fruitful results from LHCb on $B_s \rightarrow \mu\mu$, CP violation in $B_s \rightarrow J/\psi\phi$, and many other topics.

Higgs boson searches are gaining in both sensitivity and breadth; gaps are being plugged. In addition to the discovery of the Higgs at the LHC (unless Fermilab finds it first!), we can look forward to measurements of σ_T , flavor, top, Higgs, new particles and forces.

Discussions of a super-B-factory, possibly near Frascati, are maturing.¹⁵⁴ Such a machine might solve the $b \rightarrow s$ penguin problem once and for all. With a luminosity approaching 100 times current values, it would permit tagging with fully reconstructed B 's all those final states now studied with partial tags. Upgrades of KEK-B and LHCb also are being contemplated. Finally, neutrino studies¹⁵⁵ (near-term and more ambitious) and the ILC are also on our horizon. Our field has much to look forward to in the coming decades.

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